Final Report

Seismic Attenuation and Hazard in the Central and Eastern U.S.

Central and Eastern U.S. Award #: GP14AP00036

Principal Investigators: Eric Sandvol

Term: March 31st, 2015-June 31st , 2016

Funded Expended: $38,185

Dept. of Geological Sciences, University of Missouri
101 Geology Building, UMC, Columbia, MO 65211, USA
Phone: (573) 884-9616; Fax: (573) 882-5448
sandvole@missouri.edu
Key Words: site response, amplification, fundamental frequency.

A. Final Report: Seismic Attenuation and Hazard in the Central and Eastern U.S.

ACCOMPISHMENTS

During this project, we have focused on calculating the site response (the amplification and fundamental frequency) using two methods: The horizontal to vertical spectral ratio, and the Reverse Two Station Methods. The result was presented as a 3-D surface and evaluated by applying a correlation algorithm. Shear wave velocity for upper 30m, topography and attention values were tested as potential proxies for site amplification; in other words we examined the correlation between the measured site amplification and these parameters. Then we displayed the results as points. Each point represents the site effect of each station. This way apparently was convenient to evaluate and discuss the results. In addition, we have compared the results of the two methods by calculating the differences after normalizing the values between 1 and -1.

Introduction

Earthquakes within the Central and Eastern U.S. (CEUS) pose a different kind of threat than earthquakes in the western U.S. due to the relatively low attenuation at high frequencies that occurs for wave propagating across tectonically stable regions such as the central U.S. The far field effects of intraplate earthquakes will be caused by the efficient generation and propagation of regional waves, especially Lg, which is generally the largest amplitude high frequency ($f > 0.5$ Hz) regional seismic phase. Lg will most likely be responsible for all of the far field damage from a large earthquake in the midcontinent. Hence, the ground shaking at both regional and local distances likely pose a significant seismic hazard in this region. An Lg Q model that can reliably predict Lg amplitudes is critical in estimating the site response and understanding the far field seismic hazard. The goals of this project is to measure the site amplification and attenuation of high frequency regional phases in the Central and Eastern U.S in using seismic data collected from USArray TA stations and by applying a straight forward Reverse Station (RTM) approach. Furthermore, we have tested the stability of our large scale RTM site amplification model using the Horizontal over Vertical Spectral Ratio (HVSR) for regional paths across the entire Central and Eastern U.S (CEUS). This project can help in mitigating the seismic risk by better understanding the far field effects of such earthquakes due to both path-based attenuation and localized site amplification.

Methods

Estimating the site response, the amplification and the fundamental frequency, requires eliminating the path and source effects. The most efficient method to remove the path and source effect and study the site effect is the referenced method or Standard Spectral Method (SSR), introduced first by Borcherdt (1970). It depends on an available geological data set describing the local sites, which is unfortunately not available for most of the stations deployed in the TA array. Therefore, HVSR method was used to make a direct comparison with the RTM method. .

HVSR Method

Nakamura (1989) pointed out that in thick sedimentary basins, the peak spectral ratio of the Horizontal Vertical Spectral Ratio of the ambient seismic noise measurements correlates with the peak of the fundamental resonance frequency. Mostly, ambient noise consists of Rayleigh waves, which is the surface waves affected by the subsurface geology. Lermo and Chavez-Garcia (1993) proposed applying Nakamura method on the shear wave part of weak-motion earthquake data. This relatively new application of HVSR technique combines two techniques: the receiver function (Langston et al. 1979) using the H/V ration to estimate the velocity structure model, and HVSR technique of Nakamura (1989, 1996). Zhao et al. (2006) and sokolove et al. (2007) show that HVSR is reliable for sedimentary layers at recording sides. Parolai et al. (2007) shows the similarity between the HVSR and SSR methods. Although HVRS method shows stable results and correlates with the surface geology appropriately, it has xome few limitations: applying this method on P-waves contributes in an inconsistent result, the fundamental resonance frequency can underestimate the amplification factor, and this method cannot be applied on rock sites because the amplification will be unity.

The spectral ratio of vertical motion at the surface and at the bedrock, and the spectral ratio of the horizontal ground motion at surface and bedrock at a certain depth have been calculated to predict the amplification of both components; however, the vertical ratio that represents the amplitude effect should not be amplified by the sediment layer, except possibly for Rayleigh waves. The ratio then of the horizontal to vertical is an improved or modified site effect. The assumption that horizontal vertical ratio on the bedrock equals unity can be reasonable if we suppose that the bedrock underneath the sediments is a reference site, so the vertical and horizontal components are not affected by any amplification resulted from unconsolidated structure.

Reverse two station method

The amplitude of a seismic wave may be described by an exponential attenuation equation that accounts for both geometric spreading and attenuation,

$$A(f) = I(f)E(f)S(f)G(\Delta)\exp\left(-\frac{\pi f \Delta}{vQ(f)}\right) \tag{1}$$

where A is the observed amplitude between source and receiver for a wave of frequency f recorded at distance Δ. Here, I is the instrument response, E is the source spectra, S is the site amplification response, v is the wave group speed, and G is the geometric spreading function that is described primarily by an exponential decay with distance. For cylindrical spreading, the exponent should be 0.5 and for spherical spreading it is 1.0. The attenuation quality factor, Q, can be assumed to be frequency dependent, $Q = Q_0 f^{\eta}$ with Q_0 being the quality factor at 1 Hz, f the wave frequency, and η describing the frequency dependence. Values for Q_0 and η depend on the type of wave used but generally η lies between zero and one. Our frequency dependent tomographic Q models are based on these equation. The algorithm we have chosen to tomographically map variations in frequency dependent Q is the LSQR algorithm developed by Paige and Saunders, 1982. The big advantages to using the Reverse Two-Station method (RTM) is that we are able to isolate the frequency dependent station and source portions of regional phase spectra. Rather than multiply the reversed two station amplitude spectra, if we divide them we can obtain the following relationship:

$$\ln(S_i) - \ln(S_j) = \frac{1}{2}\ln\left[\frac{I_j A_{ai} A_{bi}}{I_i A_{aj} A_{bj}} \left(\frac{\Delta_{ai}}{\Delta_{aj}}\right)^{n} \left(\frac{\Delta_{bi}}{\Delta_{bj}}\right)^{n}\right] . \quad (2)$$

where the SS terms are the frequency dependent site amplifications for a given station. This problem has a unique solution if we are able to find a few particular reference stations between which the variations of site amplifications are negligible. We apply the LSQR method to calculate the lateral variations in site amplification for each station.

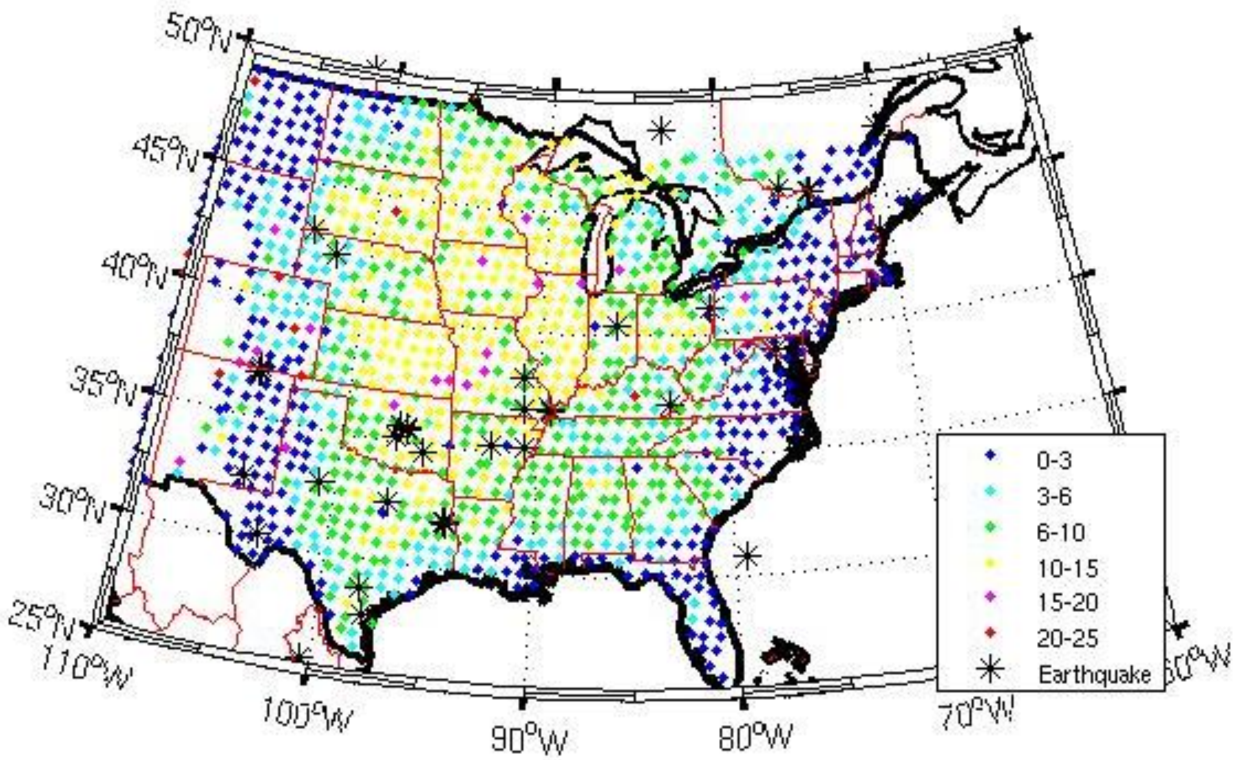

Figure 1 Station distribution over the central and eastern United States. The colour represents

the number of the seismic records in each station. The earthquake used in the HVRS method. The red line is the state boundaries.

Results

Estimating the ground motion was investigated by using HVSR method. The analyzed data windows were chosen between S-waves arrival time and end of the records. The calculated H/V ratio showed low amplification along the Appalachian, igneous and metamorphic rocks, and high amplification to the north, which correlates with the Central lowland comprising of sand and gravel deposits generally from a glacial origin figure (2). H/V ratio varies from event to others in the same seismic station. The

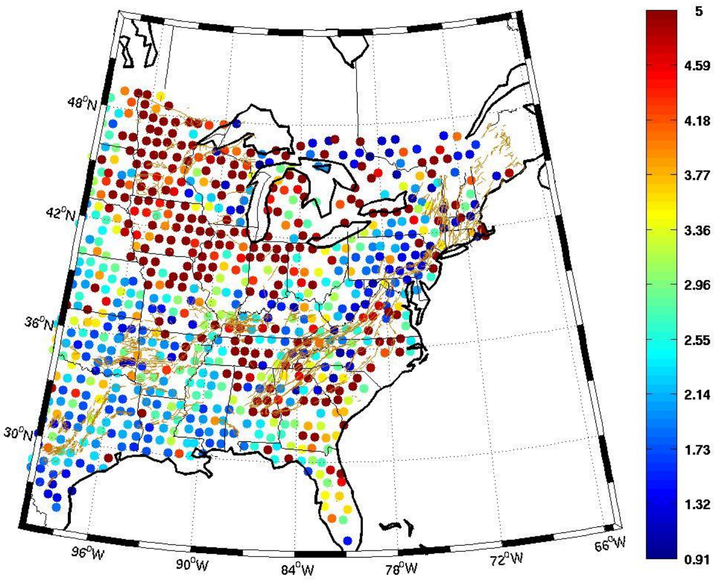

Figure 2. The amplification values from HVSR method.

shown in the southeastern the study region comparing with the northern and central part because of the seismic data distribution figure (1). While the fundamental frequency F0 has high values (6-12 Hz) along the Appalachian which increases from Crystalline to the basins Appalachian and high values in the eastern part of the Central lowland, F0 has low values (2-4Hz) along the Mississippi embayment and coastal plain figure F3). Correlation between attenuation factor Q and the amplification result shows a positive correlation northern part of USA in addition to the central USA. In other words, this region examines high amplification rates with low attenuation rate. The negative correlation along the Mississippi embayment that means the high amplification rates coincide with high attenuation.

Shear wave surface velocity for upper 30m considers a good proxy for site amplification in Geotechnical Engineering. Comparing the H/V ratio with the V30m shows a very good fit Figure (4). In addition, correlating the amplification result with the Digital elevation model and the slop shows that a positive correlation along the high elevation and high slop. For example, Appalachian and white mountain. A negative correlation was observed along the Mississippi embayment and delta. The RTS used to calculate the site response figure (5). Figure (6) shows the differences in result between HVSR and RTS method. We accepted values between (-0.5 0.5). By applying the normal cumulative distribution function, the probability that the differences of the two methods from a standard normal distribution will fall on the interval (-0.5 0.5) is 77% figure (7).

Distance and the azimuth effect on the site response (amplification and frequency) were explored by relating each of the amplification and the fundamental frequency F0 versus the distance and the azimuth for all the seismic records. The results show: the density histogram of the distances shows a high value within [600-1100] Km.. The range of distance may be account for data distribution. The density histogram of amplification, with bar width 0.5, shows a high density between 3.0 and 5. When HVSR ~2 means there is no amplification. There is a long degreasing rend between HVRS amplification and distance, especially with a distance > 1400 Km. This result suggested a rough negative correlating between the distance and the amplification. There is no a specific apparent trend for the fundamental frequency versus the distance**.** In addition, depicting the back azimuth against the amplification and fundamental frequency did not show any specific trend.

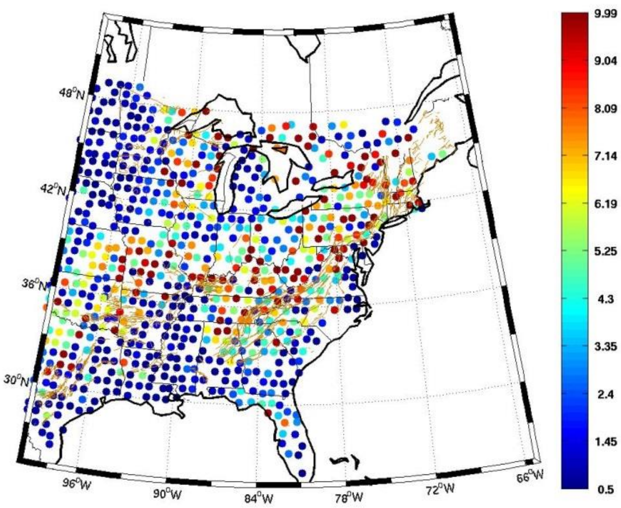

Figure 3.Peak Fundamental frequency (F0) from the HVSR method.

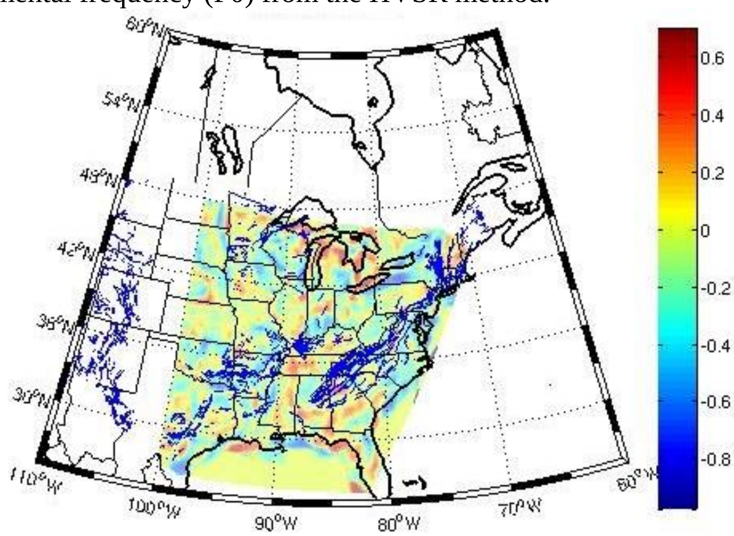

Figure 4. The correlation values between the Amplification from HVSR method and V30m

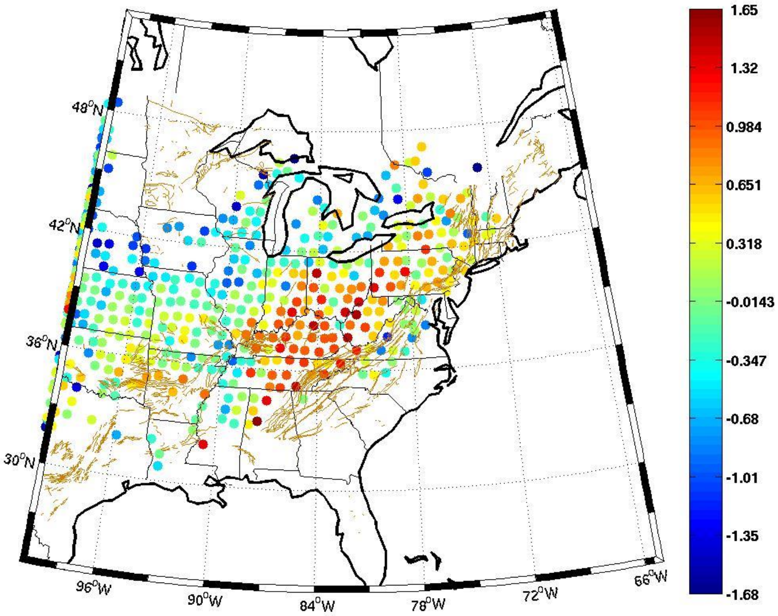

Figure 5. The site amplification terms from Reverse Two-Station Method (the red regions are regions with large site amplification while the blue are regions with strong deamplification)

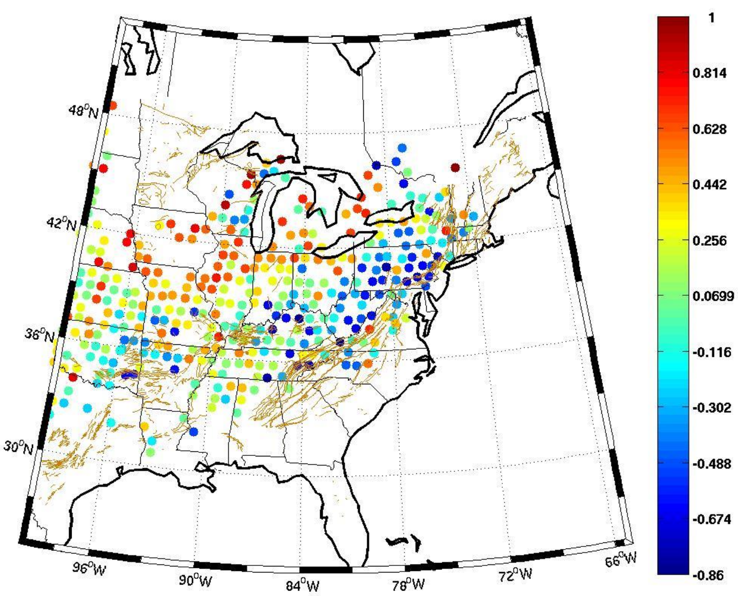

Figure 6. The differences in site amplification terms from Reverse Two-Station Method and the HVSR method (the range between 1 and -1).

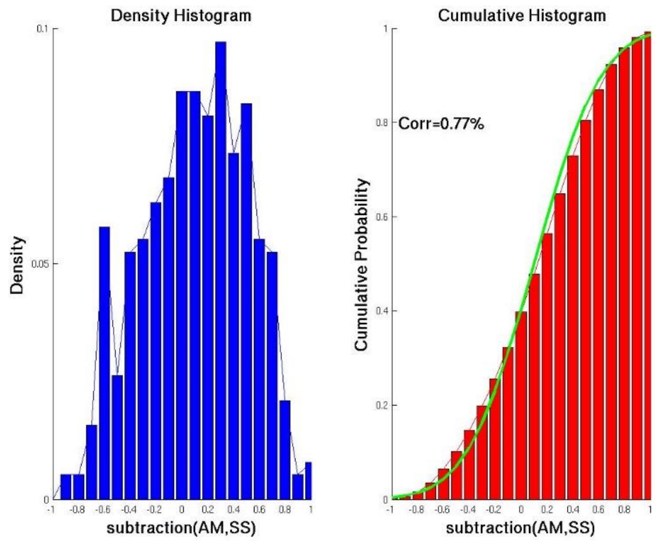

Figure 7. The probability of the differences between the RTS and HVSR methods which fall on the interval (-0.5 0.5). (AM) amplification from HVSR, SS the amplification form the RTS.

Discussion and Conclusions

The shear wave velocity for upper 30 m provides us with a potential proxy for site amplification because of its strongly impact on the seismic wave propagation in the upper crust. The inconsistent correlated result between the V30m and the site amplification could be relating to a noisy V30m values since the shear velocity values used in this study came from both wells and the gradient topographic data. In addition to inadequate, imprecise data, the unexpected amplification values in some region could be due to the rock fractionation causing velocity contrast between the bedrock and the weathered sediments.

Zandieh et al. (2011) suggested $F_0 < 5$ Hz, amplification 1.3-4 for NMSZ region, and our results show $F_0 < 4$Hz with amplification 2-4 for the same region. We do not have a reliable detailed unconsolidated sedimentary thickness data across the CEUS; however, Mucciarelli & Gallipoli (2004) examined shear waves velocity for upper 10m and compared with Vs30m. They claimed that there is no a significant difference in predicting site effect between the two velocities. Hence, using this Vs30 is likely a relatively reliable source for comparison with our estimates of site amplification. Our preliminary results suggest that in the CEUS, Vs30 does not provide a very reliable estimate for site amplification.

Examination the amplification and frequency versus the distance and the back azimuth shows a tentative trend with the distance and it did not suggest any clear trend with respect to the backazimuth, which is likely due us including broad range of frequencies in the processing or because these parameters are independent of one another. In the northern study region, the large discrepancy of the estimated site amplification using HVSR and RTM can possibly be attributed to presence of ubiquitous glacial deposits. It is not yet clear precisely how the glacial deposits are influencing the site amplification and it may be that our lack of data in this region is soley responsible for this difference.

B. PLANNED RESEARCH:

Using the dense coverage of the TA component of USArray permanent short period and broadband stations, our research will be focusing on the following aspects:

- resolving the discrepancy in site amplification between our new RTM method and the HVSR method by adding additional paths from new events in the northern and eastern part of the country
- Extending the frequency of the initial Reverse Two Station Lg Q model up to 8 Hz, which will be more comparable to the HVSR results. Therefore, extending the site amplification terms to frequencies that are potentially more important for earthquake hazard assessment. As a result, the efficiency of HVSR method for site amplification across the CEUS will be tested.
- Determine the one dimensional attenuation for local phases Pg and Sg for regions will large amounts of local recordings such as the NMSZ and central Oklahoma.. In addition, we will use the H/V ratio of the high frequency P-waves of local seismic data to calculate the shear wave velocity, which can be used to evaluate the site response results in in this region (Ni et al., 2014)..
- Comparing the local site response result with the regional result.
- Calculating synthetic seismograms for several simple 3D models (basin structure, water saturated sediment over Precambrian basement, and glacial till over bedrock) in order to understand the physics of site amplification at higher frequencies.

C. Publications/Presentations

Yassminh,R. and Sandvol, E., Site Response in the Central and Eastern United States, 2015 Seismological Society of America Meeting, Pasadena, CA.

D. Problems

None

E. References:

Al Shukri, H.J., and Mitchell, B.J., 1987, Three-dimensional velocity variations and their relation to the structure and tectonic evolution of the New Madrid seismic zone: Journal of Geophysical Research, B, Solid Earth and Planets, v. 92, p. 6377-6390.

Bally, A.W., C.R. Scotese, and M.I. Ross, 1989, North America; Plate-tectonic setting and tectonic elements, in A.W. Bally and A.R. Palmer, ed., The Geology of North America; An Overview: Boulder, Colorado, *Geological Soc. of Am.*, V. A, p. 1-15.

Bao, X., E. Sandvol, J. Ni, T. Hearn, Y. Chen, and Y. Shen, 2011, High resolution regional seismic attenuation tomography in eastern Tibetan Plateau and adjacent regions, *Geophys. Res. Lett.*, 38, L16304, doi: 10.1029/2011GL048012.

Bendick, R., R. Bilham, E. Fielding, V. K. Gaur, S. Hough, G. Kier, M. N. Kulkarni, S. Martin, K. Mueller and M. Mukul, The January 26, 2001 "Republic Day" Earthquake, 2001, India. *Seism. Res. Lett.*, 72(3), 328-335.

Benz, H., A. Frankel, and D. Moore, 1997, Regional Lg attenuation for the continental United States, *Bull. Seism. Soc. Am.*, 87, 606-619.

Bijwaard, H., W. Spakman, and E. R. Engdahl, 1998, closing the gap between regional and global travel time tomography. *J. Geophys. Res.* 103, 30055-30078.

Boore, D.M., and Atkinson, G.M., 2008, Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s: Earthquake Spectra, v. 24, no. 1.

Boore, D.M., Joyner, W.B., and Fumal, T.E., 1997, Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes—A summary of recent work: Seismological Research Letters, v. 68, p. 128–153.

Borchderdt, R.D., 1970, Effects of Local Geology on Ground Motion Near San Francisco Bay, Bulletin of the Seismological Society of America, 60 (1), pp. 29-61.

Campbell, K.W. and Bozorgnia, Y., 2008, Ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10.0 s: Earthquake Spectra, v. 24, no. 1.

Chiu, J.M., Johnston, A.C., and Yang, Y.T., 1992, Imaging the active faults of the central New Madrid seismic zone using PANDA array data, The New Madrid seismic zone, Volume 63; 3: El Cerrito, CA, United States, Seismological Society of America, p. 375-393.

Cong, L., Mejia, J., and Mitchell, B.J., 2000, Attenuative dispersion of P waves in and near the New Madrid Seismic Zone: Bull. Seism. Soc. Am., v. 190, p. 679-689.

Erickson, D., D. E. McNamara, and H. M. Benz,2004, Frequency dependent Lg Q within the continental United States, *Bull. Seismol. Soc. Am*. 94, 1630–1643.

Ervin, C.P., and McGinnis, L.D., 1975, Reelfoot Rift; reactivated precursor to the Mississippi Embayment: Geological Society of America Bulletin, v. 86, p. 1287-1295.

Frankel, A., 1991, Mechanisms of seismic attenuation in the crust: scattering and anelasticity in New York State, South Africa, and southern California, Journal of Geophysical Research, 96 (B4), pp. 6269-6289.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hopper, M., 1996, National Seismic Hazard Maps—Documentation June 1996: U.S. Geological Survey Open-File Report 96–532.